Robust methods of control for power system damping

by Fereshteh Fatehi

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering
Montana State University

Abstract:
This thesis is concerned with development of robust controller strategies which can be applied to static var compensators (SVC) in order to dampen low-frequency interarea oscillations in noisy multimachine power systems.

Two robust control strategies, adaptive and nonadaptive, are developed. The adaptive controller includes an on-line real-time recursive extended least-squares identifier to determine parameters of the system and noise model; the model parameters are used in a real-time control-design algorithm to obtain digital controller parameters; and the resulting digital control algorithm uses both system outputs and past control actions to generate control signals for the process. The nonadaptive design technique is based on combined system identification and controller design process. An iterative closed-loop identification method is used to find a linear model for the power system. To make the controller more robust to plant parameter variation and unmodeled dynamics, a linear quadratic Gaussian controller design method with loop transfer recovery (LQG/LTR) based on a generalized technique for the nonminimum phase (NMP) power system model is used to design the controller.

Detailed simulation results are presented that show the feasibility and the properties of both robust control schemes.

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Electrical Engineering

MONTANA STATE UNIVERSITY

Bozeman, Montana

February 1995

APPROVAL

of a thesis submitted by

Fereshteh Fatehi

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

3/9/95 — Date

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ACKNOWLEDGMENTS

I would like to express my gratitude to Professor Donald A. Pierre, my principal advisor, for his guidance, continuous support and constructive criticism throughout my studies and the writing of this thesis. I would also like to thank Dr. James Smith and Dr. Hashem Nehrir for their suggestions and help concerning this research. To the rest of my committee, Dr. Byron Bennett, Dr. Curtis Vogel and Dr. William Hiscock, thank you for the time you spent offering advice when it was needed. I would like to thank Dr. Roy Johnson for the computer support that he has provided. Many others also have been helpful to the work of this thesis including Mr. Stott Woods, Dr. Iraj Sadighi and Dr. Dan Trudnowski whose codes in adaptive control were used in this thesis.

The financial support of the Montana State University Engineering Experiment Station, the Montana Electric Power Research Association, the Bonneville Power Administration and the National Science Foundation is appreciated.

Finally, I would like to express my appreciation to my parents, my sister Fahime, my brothers and my best friend Maryam for their support throughout my studies.

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ABSTRACT

This thesis is concerned with development of robust controller strategies which can be applied to static var compensators (SVC) in order to dampen low-frequency interarea oscillations in noisy multimachine power systems.

Two robust control strategies, adaptive and nonadaptive, are developed. The adaptive controller includes an on-line real-time recursive extended least-squares identifier to determine parameters of the system and noise model; the model parameters are used in a real-time control-design algorithm to obtain digital controller parameters; and the resulting digital control algorithm uses both system outputs and past control actions to generate control signals for the process. The nonadaptive design technique is based on combined system identification and controller design process. An iterative closed-loop identification method is used to find a linear model for the power system. To make the controller more robust to plant parameter variation and unmodeled dynamics, a linear quadratic Gaussian controller design method with loop transfer recovery (LQG/LTR) based on a generalized technique for the nonminimum phase (NMP) power system model is used to design the controller.

Detailed simulation results are presented that show the feasibility and the properties of both robust control schemes.

CHAPTER 1

INTRODUCTION

Power systems commonly exhibit low-frequency electromechanical oscillations particularly when operated under conditions where large power transfers are being made over long transmission lines. Many types of unavoidable system disturbances can cause electromechanical oscillation, and severe oscillations can decrease the life of generators and limit the amount of transferable power over transmission lines.

There are two types of electromechanical oscillations: local modes (1 to 3 Hz) and interarea modes (0.1 to 1 Hz). A local mode of oscillation occurs when a single generator swings against the system while an interarea mode of oscillation occurs when a group of generators swing together against other groups of generators.

Because power systems generally are large nonlinear time-varying systems, it is often difficult to dampen these oscillations. A static var compensator is one of several devices that can be used to enhance damping in a power system. Other devices are power system stabilizers (PSS), high voltage DC (HVDC) converters, and electronically controlled braking resistors.

Since a static var compensator (SVC) can modulate the power flow on the line where the controller is located, the controller can have a much greater effect on some of the interarea modes. Also an SVC may be more feasible to use for a utility company that is primarily a power transmission company and not a power generation company.

The objective of this thesis is to develop control strategies which can be applied to a static var compensator (SVC) in order to dampen low-frequency interarea oscillations in multimachine power systems. The primary purpose of most SVC's is local bus voltage control. An SVC acts effectively as a thyristor controlled variable shunt susceptance in the power network. In response to an input signal the shunt susceptance can be changed to modify the reactive power and voltage magnitude at the local bus. Interarea damping control can be added as a supplementary control loop using one of the system signals which has good controllability and observability characteristics for several interarea modes. It is expected that the design processes that are being developed will not be unique to SVC's but may also be applied to many other power system devices.

In this thesis two approaches to robust controller design are presented. Both of these approaches attempt to dampen low-frequency oscillations in a noisy multimachine power system environment.

The first approach is concerned with the ability of an advanced self-tuning adaptive controller to dampen low-frequency oscillations in large interconnected power systems when various levels of noise are present. The controller includes an on-line real-time recursive extended least-squares identifier to determine parameters of the system and the noise model; the model parameters are used in a real-time control-design algorithm to obtain digital controller parameters; and the resulting digital control algorithm uses both system outputs and past control actions to generate control signals for the process.

The second approach is a nonadaptive design technique for power system damping controllers. This nonadaptive technique is based on combined system identification and controller design. An iterative closed-loop identification method is used to find a linear model for the power system. To make the controller more robust to uncertainty, plant variations, and unmodeled dynamics, a linear quadratic Gaussian controller design method with loop transfer recovery (LQG/LTR) based on a generalized technique for the nonminimum phase (NMP) power system model is used to design the controller.

The simulations discussed in this thesis are based on the ETMSP software developed by the Electric Power Research Institute (EPRI) [1]. The extended/midterm stability program (ETMSP) is a time-domain simulation program for stability analysis of large power systems. In order to access ETMSP signals a subroutine had to be added to the program. The basic function of this subroutine is to allow access to any system signal within the ETMSP program. It also allows modification of the controller reference signals and variables. A manual is available for detailed information about the subroutine and state variables [2].

To evaluate the control design methods, they are simulated in realistic computer models of large power systems. Large power systems, such as the western grid of the United States, contain hundreds of generators and transmission lines. To achieve reasonable simulations in terms of time and cost, reduced-order systems are required that retain key attributes of the large systems. In Chapter 2 an approach to obtaining reduced-order power system test models is described. The approach has been developed and modified over the past few years at MSU. By using the approach, many essential features of large power systems are retained in significantly smaller power system models.

The remaining part of this chapter is organized into four sections. A brief review of SVC control for power system damping is given in the first section. Robust adaptive control for noisy power systems is introduced in section two, and robust nonadaptive control concepts are introduced in section three. In the last section the organization of the remaining thesis is outlined.

SVC Control for Power System Damping

The need to improve damping in power system networks has been growing over the years [3]. Poorly damped oscillations have been noticed in power systems in many parts of the world. The major factor contributing to these oscillations is often the use of long transmission lines carrying large power flows from one area of a system to another. In some cases this occurs because generating facilities are located in remote areas from major load centers. Undamped or poorly damped oscillations are often the limiting factor in determining how much power can be transported from one area of a system to another. Smith [4] gave a good review of damping controller designs using static var compensators which appeared in the literature prior to 1988. This section gives a brief review of some papers in this area which have been published recently.

Gyugyi [5] has written a paper about fundamentals of thyristor-controlled static var compensators in electric power system applications. The first part of the paper describes methods of reactive power generation, including power circuit arrangements, basic operating principles, and the internal control mechanism necessary to provide continuously variable var output. The second part explains the functional and operating requirements of power system compensation, with respect to voltage support and stability improvement, and derives the external controls needed to meet these requirements. The third part deals briefly with the coordination of the thyristor-controlled static var compensator and conventional mechanically switched capacitors and reactors.

In [6] Lerch, et al., describe a new method which defines the phase angles of generators on the basis of voltage and power measurements at the location of an SVC. These state variables are employed for improvement of damping of power system oscillations by the SVC. The new SVC control can optimally damp active poor oscillations. The damping signal is shown to be robust in particular in the vicinity of the stability limit and has the advantage that no error signals occur at large differences in the phase angles.

Padiyar, et al., [7] consider the application of a damping torque technique to examine the efficacy of various control signals for reactive power modulation of static var system (SVS) in enhancing the power transfer capability of long transmission lines.

Larsen, et al., [8] discuss the basic aspects of applying SVC's to series-compensated AC transmission lines which creates some new application considerations. The paper presents basic information on SVC interactions with series-compensated transmission lines. There exists a potential for adverse interactions which are different from the type seen in ac systems without series compensation. Secure operation can be attained by minor modification to the SVC control system, but specific studies are suggested - at least for each different SVC control type.

Dash, et al., [9] present an adaptive stabilizer design for static var compensator control in power systems, for either voltage regulation or controlling dynamic and transient performance under abnormal conditions such as 3-phase short-circuits, voltage collapse, load shedding, etc.

Hsu, et al., [10] examine the effect of a power system stabilizer and a static var compensator on the damping of a longitudinal power system. A combination of PSS and an SVC are employed because a large generating unit which is suitable for the installation of an additional PSS is not available in the central area of the study system. Results from time domain simulations indicate that the PSS and the SVC are very effective in damping system oscillations.

Robust Adaptive Control

Adaptive control has been an area of intensive research for the past thirty years (see [11] and [12] for example) and has reached the stage where the technology can be applied to produce significant benefits in certain applications. An area in which this appears to be true is in the control of large power systems [13]. The two main approaches to adaptive control are direct adaptive control (having at most implicit parameter identification) and indirect adaptive control (with explicit parameter identification). With indirect self-tuning control, an on-line real-time identifier determines parameters of a system model, the model parameters are used in a real-time control-design algorithm to obtain digital controller parameters, and the resulting digital control algorithm uses both system outputs and past control actions to generate control signals for the process.

In large interconnected systems that contain lightly damped modes of oscillations (e.g., power systems), controllers are often added to the system to increase the damping of certain modes. These controllers must respond to system disturbances in such a way that the control signal reacts to a disturbance, adding damping, and then returns to a nominal design-center value after the disturbance in order to be ready to react in either direction for the next major disturbance. Also, the control often must be limited in its rate of change in order to minimize the excitation of higher-order modes in the system. A control law that is ideal for the above purpose is an enhanced linear-quadratic (LQ) control law [14-16] that penalizes system states, control level, and rate of change of control level. Adaptive versions of this control are generalizations of the LQ adaptive controller described by Samson [17].

In [4] and [18], an adaptive version of enhanced LQ control was used in a nine-bus power system simulation to control a static var unit; the controller was single-input single-output, and a recursive least-squares (RLS) identifier was used. In [19] the controller was structured to add damping to the system in which the primary purpose of the static var unit was voltage regulation; two system outputs were used by the controller. The use of many such controllers as power system stabilizers on generator exciters in large interconnected power systems is examined in [20-23]; benefits are shown to accrue from the use of coupling terms in local identifiers when associated generators are closely coupled in the network. While the power system simulations used in the above studies included realistic power system dynamics (nonlinear models and system faults), the simulations did not include realistic levels of power system ambient noise.

In Chapter 3, a mass-spring system with abrupt parameter changes and additive system noise is used as a test bed for an enhanced LQ adaptive controller; it will be shown that recursive extended least squares (RELS) can be beneficial to adaptive damping by determining colored noise parameters in addition to system parameters [24].

The advanced adaptive controller designed in this way is applied in Chapter 4 to dampen low-frequency oscillations in a large interconnected power system simulation. Robustness of the control is examined relative to realistic load noise and faults that change the system operating point [25].

System Identification and Robust Nonadaptive Control

This part of the thesis is concerned with the use of least squares transfer function identification methods for the design of controllers to enhance the damping of interarea oscillations in multimachine power systems. A brief history of the early developments in transfer function identification in power systems can be found in [26]. Previous work in the area has shown that numerically identified transfer function models can be very useful in a variety of power system applications [27-31]. These applications include the tuning of damping controller parameters, software validation, model validation, and on-line evaluation of power system operating conditions in general. Recent papers in transfer function identification have reported significant advantages in identifying the plant from closed-loop operation rather than from the open-loop state [32-38].

In [32] the authors suggest that identification and model-based control design have to be treated as a joint problem if they are combined to achieve a high-performance control system. Solving this joint problem with individual identification and control design methods requires an iterative approach. The proposed iterative scheme is based on a robust control design method. Each identification step uses the previously designed controller to obtain new data from the plant. The associated identification problem has been solved by means of a coprime factorization of the unknown plant. An example has given evidence of the utility of the iterative scheme.

In [33] a criterion for system identification is developed which is consistent with the intended use of the fitted model for modern robust control synthesis. Specifically, a joint optimization problem is posed which simultaneously determines the plant model estimate and control design, so as to optimize robust performance over the set of plants consistent with a specified experimental data set.

In [34] a fractional representation approach is used to state and solve the closed-loop experiment design problem in terms of variables which are at the designer's disposal: the closed-loop inputs and the initial controller. The paper states that most actual identification experiments are conducted while the system is operating under closed-loop control and that the direct application of open-loop results to the closed-loop problem generally gives unsatisfactory results. This paper therefore addresses the problem of system identification experiment design in which the system to be identified is operating in a stable closed-loop configuration.

In [35,36] the authors suggest a combined iterative control system design which couples the separate stages of model identification (using frequency weighted least squares) with controller design from this model (using frequency weighted LQG methods).

Reference [37] focuses on the extension of an iterative identification/controller design using the H_2/LQG iteration of Zang, et al., [35,36]. The paper proposes two refinements to this iterative scheme. The first refinement is to decouple the identification and controller design phases by altering the sequence of steps in a single iteration. The first part of the iteration adjusts the model, while the second part refines the controller. The second refinement is a natural extension of the first. In this refinement they focus upon the controller enhancement with respect to the achieved and designed performance. This permits the consideration of an iterative controller design without the need for model adjustment.

Linear quadratic Gaussian controller design with loop transfer recovery (LQG/LTR) is an area of feedback control theory that has recently received a great deal of attention [39-41]. For systems that are nonminimum phase LQG/LTR controller design is based on partial loop transfer recovery techniques [41-43].

Organization of Thesis

The reminder of this thesis consists of seven chapters. Chapter 2 that follows describes an approach to obtaining reduced-order power system models that retain essential features of large power systems [31].

Chapters 3 and 4 are concerned with the robustness of a self-tuning adaptive controller to dampen low-frequency oscillations in large noisy power systems. In Chapter 3 a mass-spring system with abrupt parameter changes and additive system noise is used as a test bed for the design of an enhanced LQ adaptive controller. A recursive extended least-squares (RELS) algorithm is used for identification which determines colored noise parameters in addition to system parameters [24]. In Chapter 4 the advanced adaptive controller described in Chapter 3 is applied to dampen low-frequency oscillations in large interconnected power system simulations. The controller uses a static var unit to dampen low-frequency oscillations [25].

Combined closed-loop identification and controller design is considered as a nonadaptive design technique. Chapter 5 presents an introduction to concepts and applications of least squares transfer function identification (TFI) in power systems [29]. Chapter 6 shows the effectiveness of using closed-loop identified models compared to open-loop identified models for the design of power system controllers [44]. And Chapter 7 demonstrates the robustness of a generalized LQG/LTR controller design used for damping power system oscillations [45]; two approaches to partial LTR applicable to NMP plants are described and compared. The robustness of the resulting controllers is examined relative to the amount of loop transfer recovery that is possible for the NMP plant model.

Chapter 8 summarizes the contribution of this thesis and discusses some research topics that merit additional study.

CHAPTER 2

LOW-ORDER POWER SYSTEM MODEL

This chapter is concerned with the development and evaluation of a low-order power system transient stability test model which has dynamic characteristics similar to those exhibited by a full-order model [31]. The model is designed to have dynamic characteristics resembling those of a 2000 bus model of the western North American power system. The objective of the low-order modeling effort is to create an interesting and realistic environment in which to develop and test dynamic control strategies. Controller designs which appear promising on the test model can then be evaluated more thoroughly on the high-order system.

One of the major difficulties in the development of realistic dynamic control strategies for large interconnected power systems is the sheer size of many modern power networks. Detailed studies of such systems require substantial computational effort as well as the analysis of volumes of output data. The dynamic vastness precludes any attempt at controller design based on full analytic modeling. The study of power system dynamics and damping control therefore generally involves numerous simulations under a variety of system conditions. For a full-order model this is inconvenient due to both the computational time involved and the difficulty of sorting through the enormous amount of data that the simulations generate. Unfortunately, when the dynamic size is reduced to that which can be analytically described, the representation of the pertinent control environment may be lost. Thus the control strategies that are developed on a low-order system may not work well when applied to a full-order system due to large differences in the control environment of the two models. The most extreme example of a low-order model which cannot reasonably represent the dynamics of a large-order system is the one-machine infinite-bus system. Although the one-machine infinite-bus system has been very useful for developing an initial understanding of power system dynamics, the control environment is much too simplistic for many realistic studies intended for application to large-order systems. For these reasons there is a need for models which are reduced in complexity from a full-order model but reasonably reflect its characteristic dynamics.

This chapter outlines the development and characteristics of one low-order test model which has been developed and modified over the past few years at Montana State University. It has been used to design and test possible methods for increasing power system damping using several strategies. These strategies include PSS design [27], SVC modulation [29], and HVDC modulation [46]. The objectives are twofold: to describe the model development; and to illustrate techniques for the analysis of control system environments which may make designing controllers more difficult in some cases than in others.

The model under discussion was derived from a 2000 bus model of the western North American power system which is used by the Western Systems Coordinating Council. It has 46 buses, 19 machines and has power flow patterns and dynamic characteristics which are similar to the 2000 bus case. It was designed to have a similar enough control environment that experimental control strategies developed for the 46 bus model can be expected to transfer reasonably well to the 2000 bus model. A highly accurate reduced model is not the objective of this 46 bus system. The primary objective is a highly reduced model retaining a few local modes and the major interarea characteristics of the original system. The simulations discussed in this work have been carried out using the ETMSP software [1].

The organization of this chapter is as follows. First, the development of the low-order model is discussed, and the low-order model is compared to the high-order model using frequency domain plots of generator speed signals. Following this the Fourier transform is briefly examined in terms of transfer function residues and damping. Also some characteristics of the low-order model are examined and compared to the high-order model using a Prony based transfer function identification algorithm.

Low-Order Model Development

The frequency response of a generator state variable typically shows a number of oscillations in the 0.1 to 1 Hz range. These oscillations - called interarea modes - involve groups of generators swinging together against machines in another area of the system. The machine states also will usually exhibit local modes; that is oscillations in the 1 to 3 Hz range which are due to the machine itself swinging against the system. Because the interarea modes involve groups of machines swinging together, they lend themselves well to being modeled in a reduced-order environment where a number of machines are represented by a single big machine. The local modes, on the other hand, are each due to the local machine interactions and so as the number of the machines being individually modeled is reduced, much of the detail of the local dynamics may be lost.

A reasonable goal, therefore, in constructing a low-order model is to reproduce the interarea interactions as well as possible and to create a single local mode on each of the machines which is similar to the modes which a machine in the high-order system exhibits. A description of the steps in constructing this low-order equivalent are listed below. Each of these steps is discussed in more detail in the subsections which follow.

1. **Geographic** - Each major area in the system is represented by at least two machines, one classical and one or more detailed. The areas are then connected by intertie lines in a similar geometry to the 2000 bus system.

2. **Powerflow** - The power flows between areas are adjusted to match those of the 2000 bus case.

3. **Kinetic Energy (KE)** - The KE (MWatt-secs) of the classical machines are adjusted to move interarea modes until they line up well with the 2000 bus case.

4. **Damping Coefficient** - The damping coefficient on each machine is adjusted until the damping of the local mode is similar to that of the relevant machine in the high-order system.

Geographic

Figures 2.1 and 2.2 are both representations of the western North American power system. Figure 2.1 shows the actual layout of the major transmission lines.

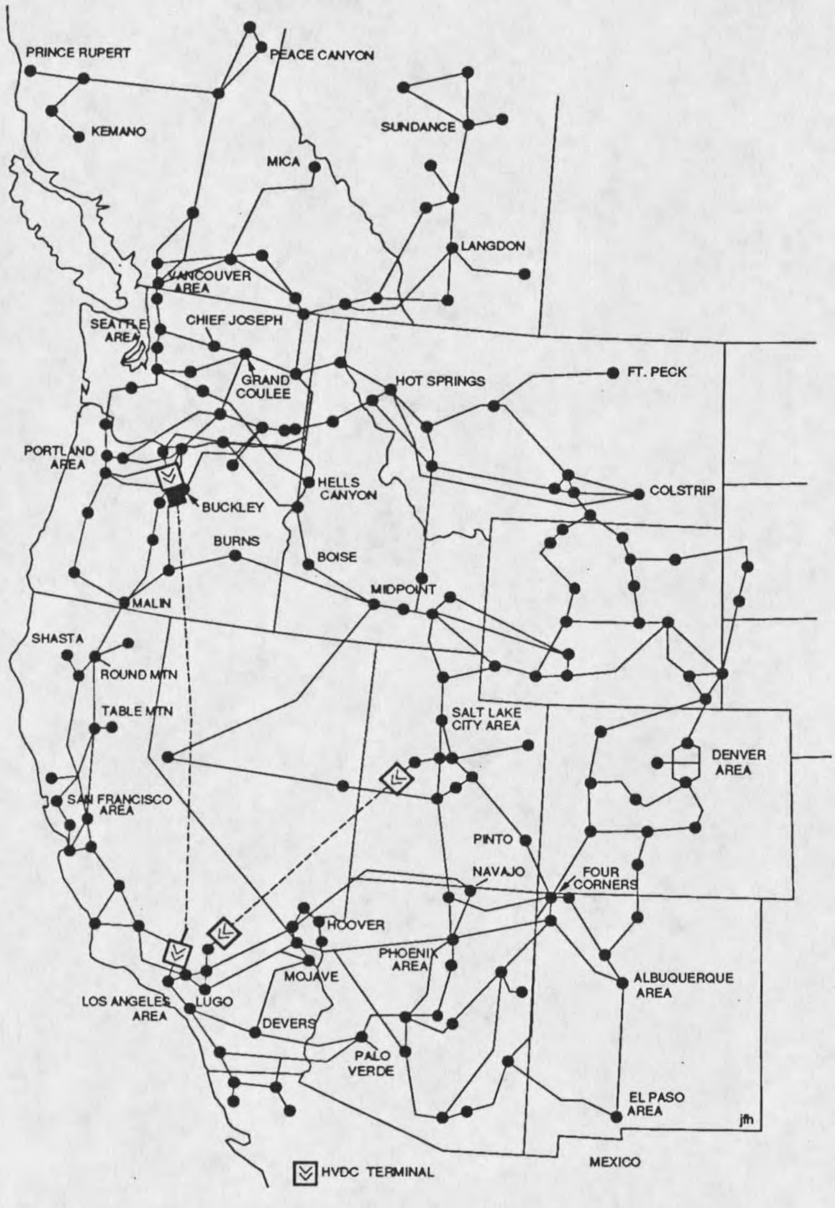

Figure 2.1. Major transmission lines of the western North American power network.

Figure 2.2 is taken from a Western Systems Coordinating Council (WSCC) bubble diagram description of a planning case and shows the ownership regions (areas) of the system and power exchange over interties. The first step in constructing